Measurement of the top pair invariant mass distribution at 7 TeV and search for new physics with the CMS experiment

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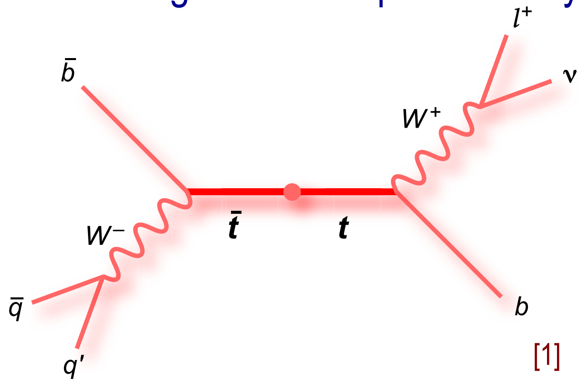
"Search for Resonances in Semi-leptonic Top-pair Decays Close to Production Threshold "
CMS-PAS-TOP-10-007 - http://cdsweb.cern.ch/record/1335720/files/TOP-10-007-pas.pdf

Introduction

Many extensions of the Standard Model predict gauge interactions whose couplings with the top quark are enhanced. The resulting new particles could show up as resonances in the $t\bar{t}$ mass distribution and not in other channels.

The search for such resonances is performed using the semi-leptonic decay of the $t\bar{t}$ pair.



[1]

BR(t→Wb) ≈ 0.99
$t\bar{t}$ semileptonic (e,μ) BR ≈ 0.3

Signature and backgrounds

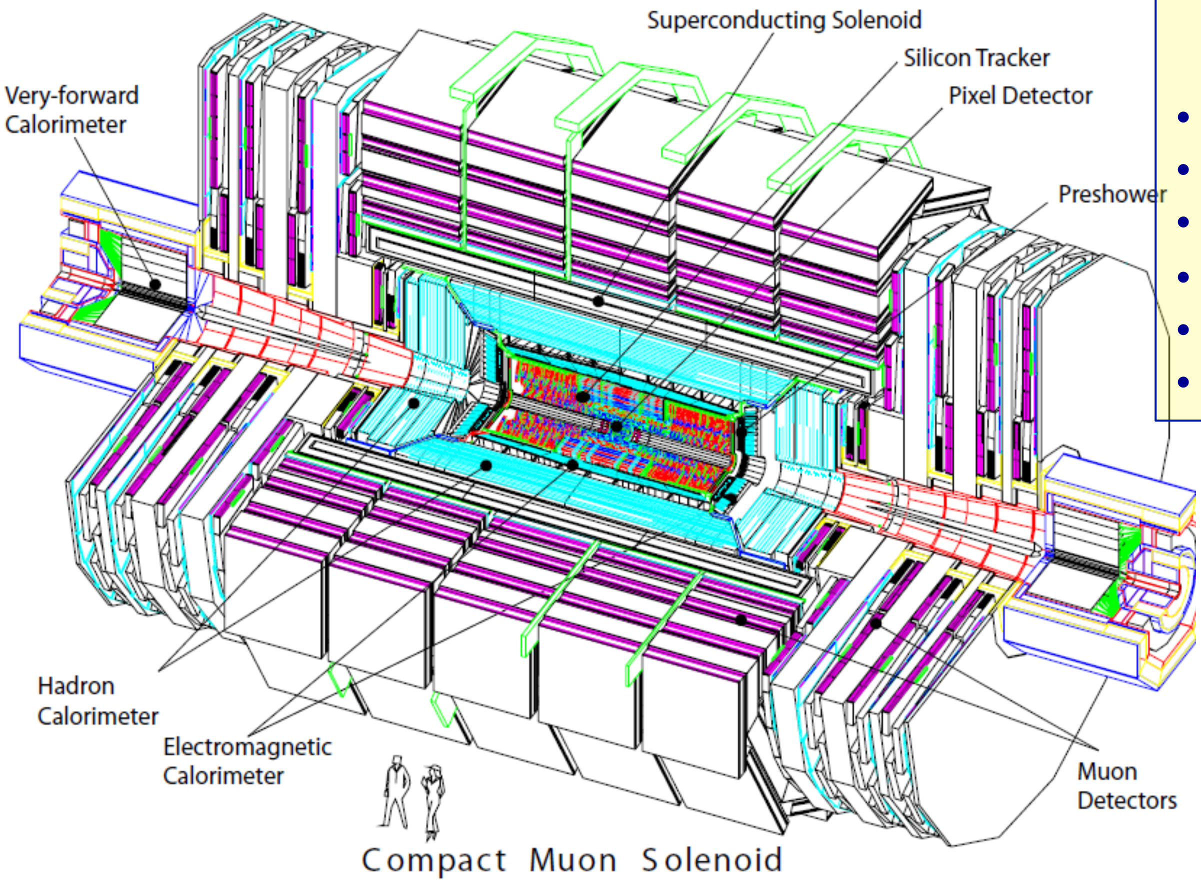
Energetic and isolated muon/electron in an energetic hadronic environment with two heavy flavour jets.

Main backgrounds:
- SM $t\bar{t}$ production
- W bosons plus jets
- Single t quark production
- QCD

QCD and W plus jets can be suppressed by requiring the lepton isolation and at least three energetic jets respectively.

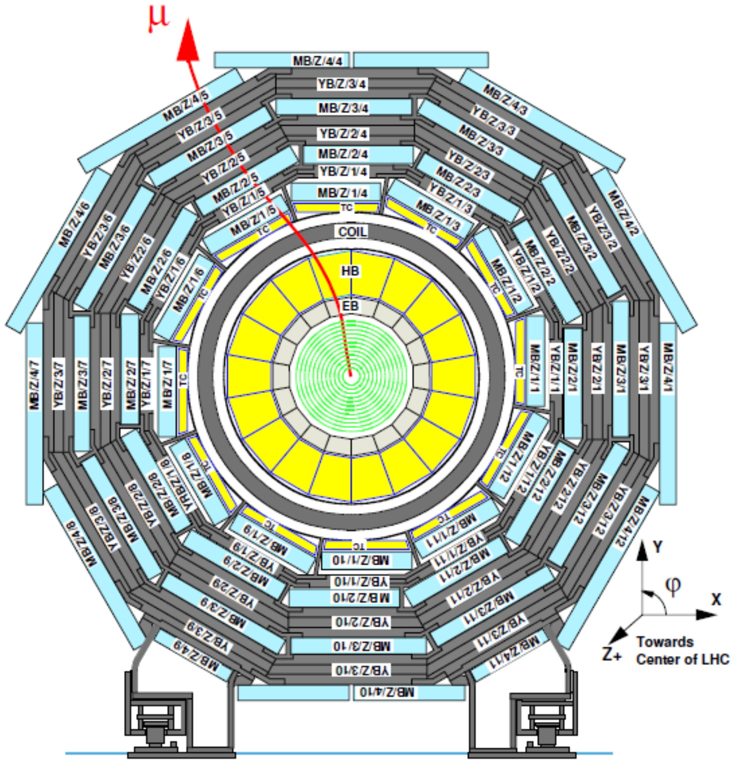
[1] http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_feynman_diagrams.html

CMS detector



CMS main features

- size: 13 m length and 6 m diameter
- ~3.8 T superconducting solenoid
- silicon tracker (pixel + strips)
- homogeneous ECAL (*$PbWO_4$*)
- plastic scintillators based sampling HCAL
- gaseous detectors based muon spectrometer



Event selection 1/2

Event selection

Trigger | Lepton quality | Veto | Jets quality

- **Trigger**
  single lepton trigger (μ or e) without isolation requirement.

Event selection 1/2

Event selection

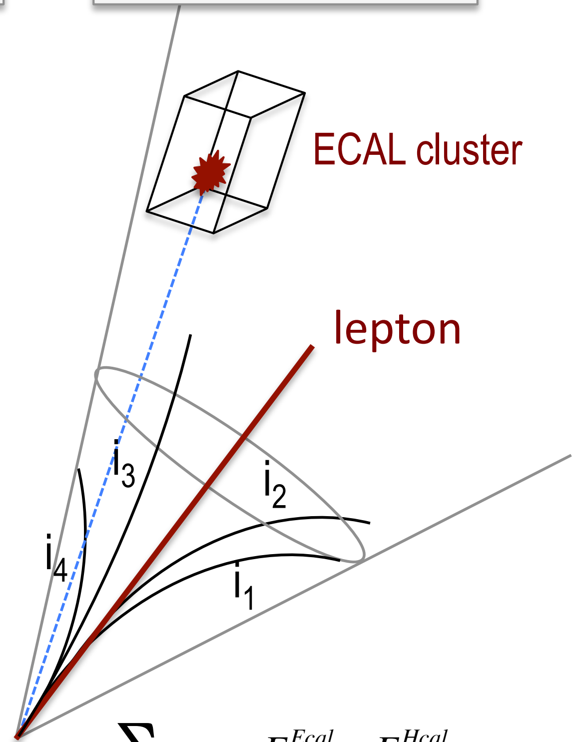
Trigger | **Lepton quality** | Veto | Jets quality

- **Trigger**
  single lepton trigger (μ or e) without isolation requirement.

- **Lepton quality**

  Muon
  global muon (reconstructed using tracker and muon chambers)
  $p_T > 20$ GeV/c ***AND*** $|\eta| < 2.1$
  recontruction quality (χ^2/ndof, # tracker hits, # of pixel hits)
  $d_{xy} < 0.02$ cm ***AND*** $d_z < 1$ cm
  relative isolation < 0.1 ($\Delta R < 0.3$)

  Electron
  $p_T > 30$ GeV/c ***AND*** $|\eta| < 2.5$ (excluding $1.4448 < |\eta| < 1.566$)
  track must have an associated hit in the first pixel layer
  no other tracks with $\Delta\cot\theta < 0.02$ and distance < 0.02 cm in the transverse plane
  relative isolation < 0.1 ($\Delta R < 0.3$)



$$\frac{\sum_i p_{i,T} + E_T^{Ecal} + E_T^{Hcal}}{p_T}$$

Conversion rejection

Event selection 2/2

Event selection

Trigger | Lepton quality | **Veto** | Jets quality

- **Veto on events with additional leptons**

  Muon
  pT > 10 GeV/c ***AND*** $|\eta| < 2.5$
  relative isolation < 0.2 ($\Delta R < 0.3$)

  Electron
  pT > 15 GeV/c ***AND*** $|\eta| < 2.5$
  relative isolation < 0.2 ($\Delta R < 0.3$)

Event selection

Trigger | Lepton quality | Veto | **Jets quality**

- **Veto on events with additional leptons**

  Muon
  pT > 10 GeV/c ***AND*** |η| < 2.5
  relative isolation < 0.2 (ΔR < 0.3)

  Electron
  pT > 15 GeV/c ***AND*** |η| < 2.5
  relative isolation < 0.2 (ΔR < 0.3)

- **Jet quality and missing energy**

  At least 3 particle flow reconstructed jets with:
  - pT > 30 GeV/c ***AND*** |η| < 2.4
  - no overlap with the lepton candidate in (ΔR < 0.4)

  correction are applied (called L2 and L3) to take into account the dependence on η and p_T
  the transverse missing energy > 20 GeV

Event classification

1. 3 jets with at least one b-jet
2. ≥ 4 jets without b-tagging requirement
3. ≥ 4 jets with one b-jet
4. ≥ 4 jets with at least 2 b-jets

for both lepton flavour ⟹ 8 categories

Mass reconstruction

It is performed in three steps:

1. leptonically decaying W reconstruction
   - missing E_T is taken as measurement of the p_T of the neutrino
   - imposing $M_{l\nu}$ = W mass a quadratic equation for the p_L of the neutrino is obtained
   - in case of no real solutions $\not{E}_T$ is minimally modified to obtain at least one real solution

2. Jets to partons association

   two jets must be associated to the hadronically decaying W and two jets must be associated to the two b quarks in the event. **All possible combinations are considered.**

Event classification and mass reconstruction 2/2

3. tt mass reconstruction and kinematic fit

for each combination the χ^2 is calculated (including neutrino solutions) and the smallest value is kept.

reconstructed observable **reference value**

$$\chi^2 = \sum \frac{(x_i^{obs} - x_i^{ref})^2}{\sigma_i^2}$$

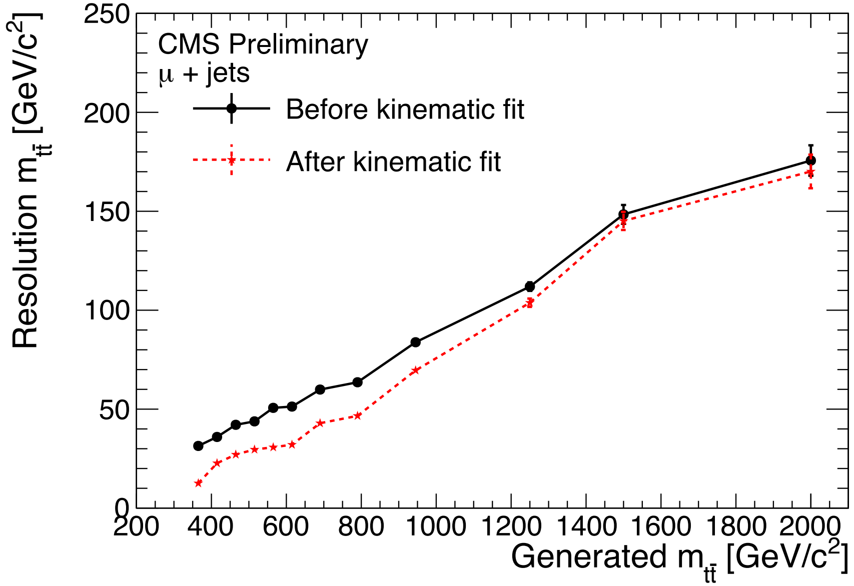
resolution

All reference values are obtained from MC simulation

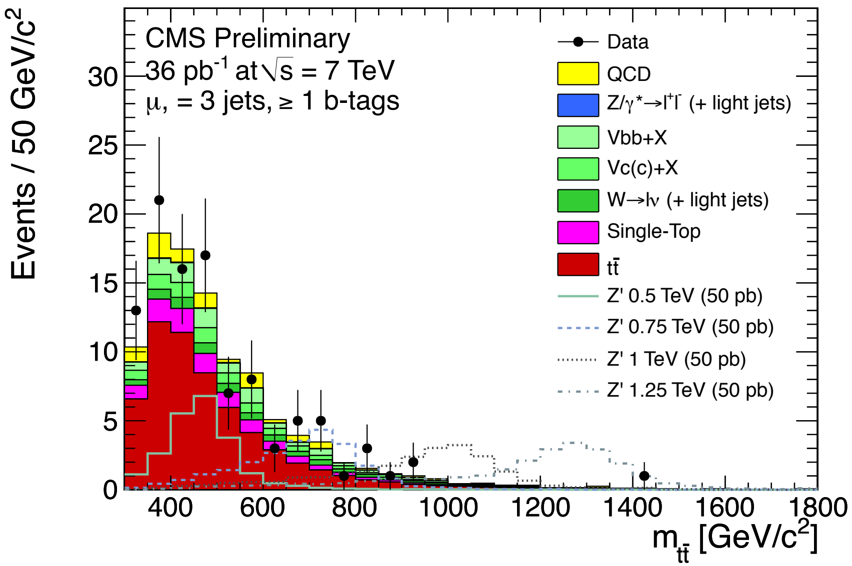
Observable
Leptonic top mass
Hadronic top mass
Hadronic W mass
p_T of tt system
H_T fraction

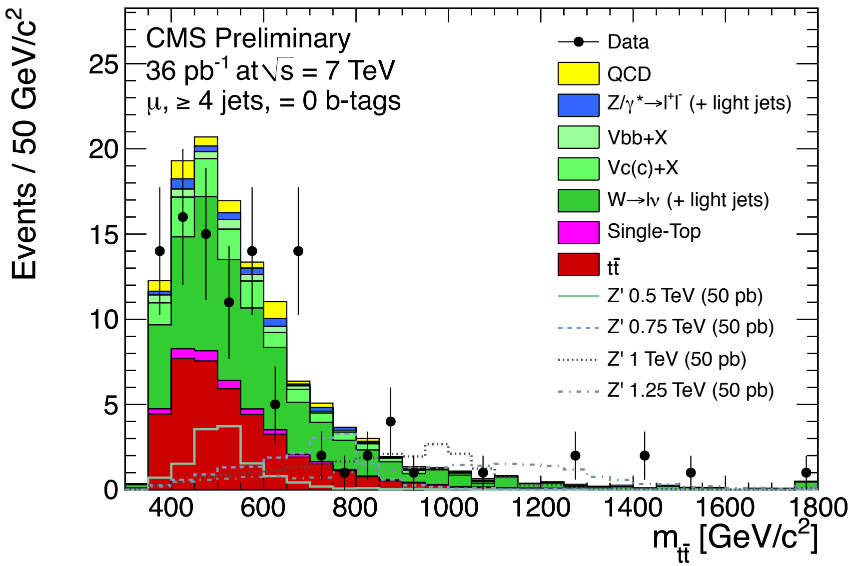
Kinematic fit is used to improve the m_{tt} measurement

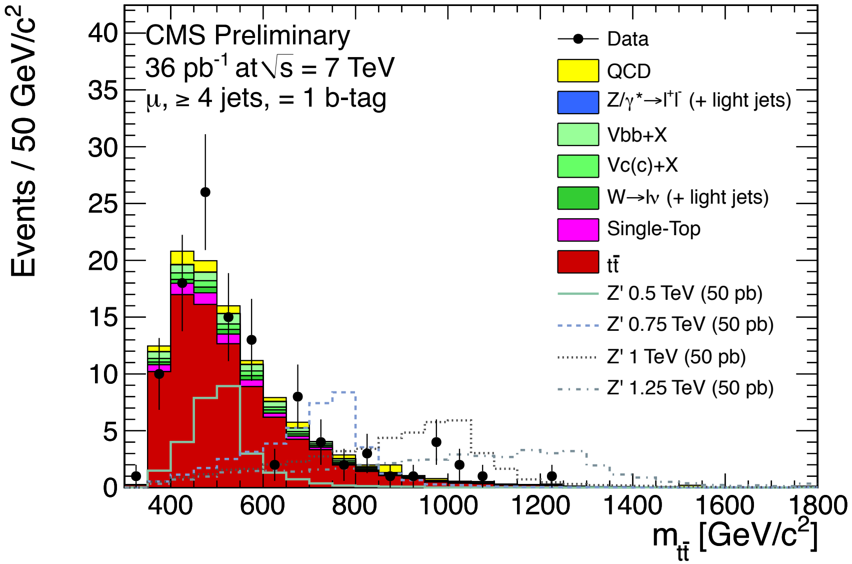
- least square method to apply kinematic contraints event by event
- the four-momenta of the reconstructed objects are varied within their resolutions
- constraints on both W and t quark mass are used

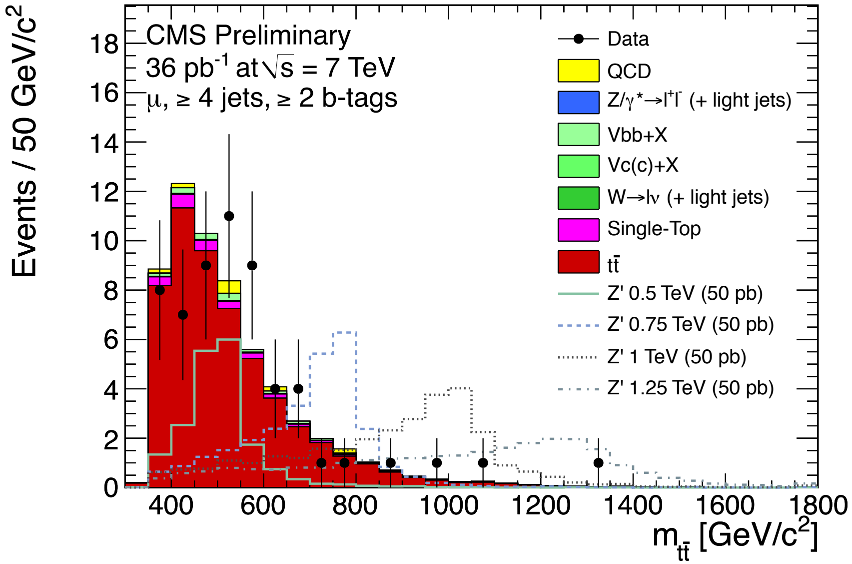


Comparison data and MC – muon case

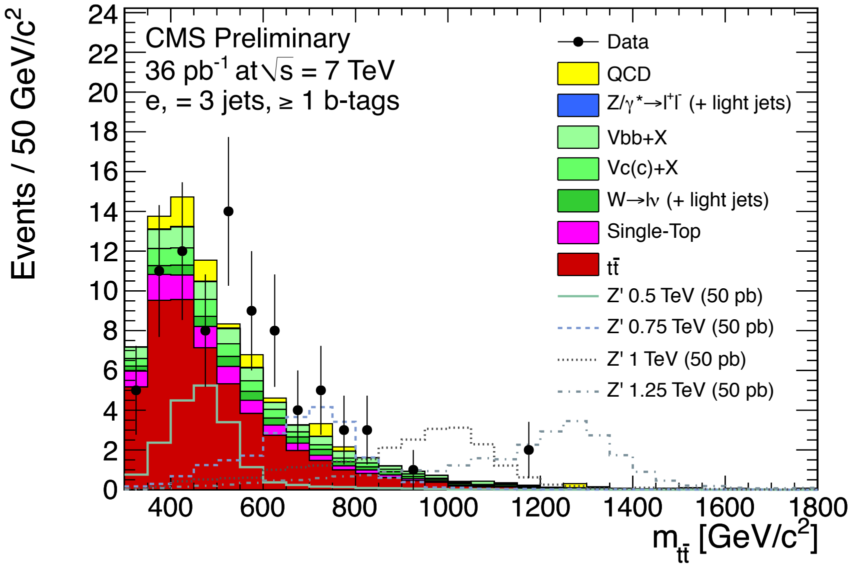


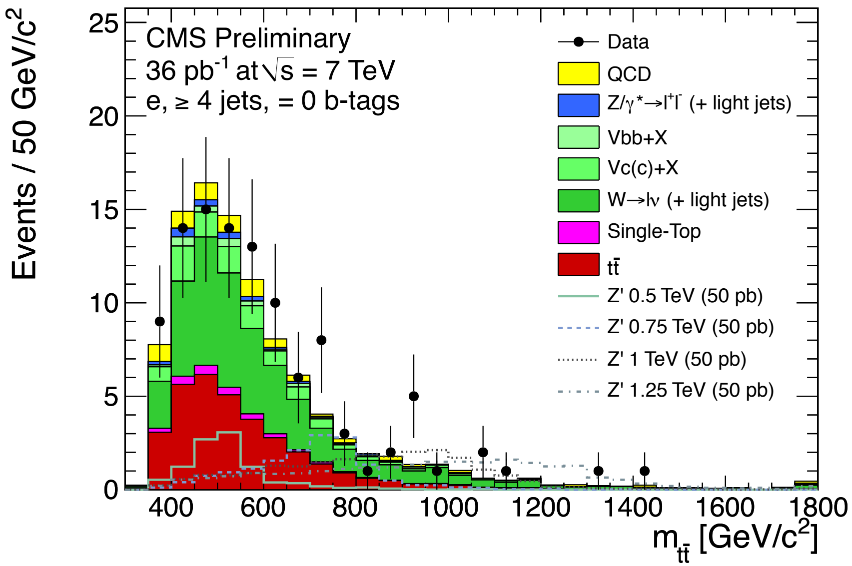


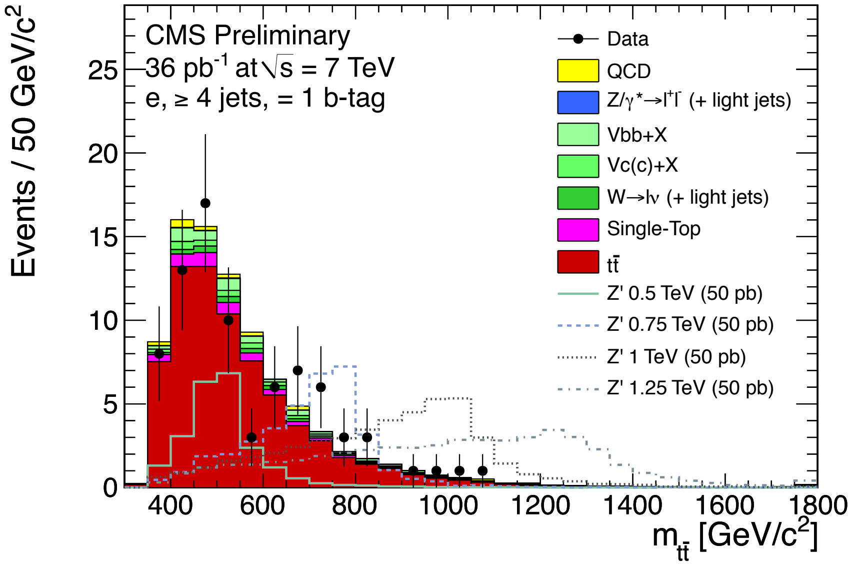


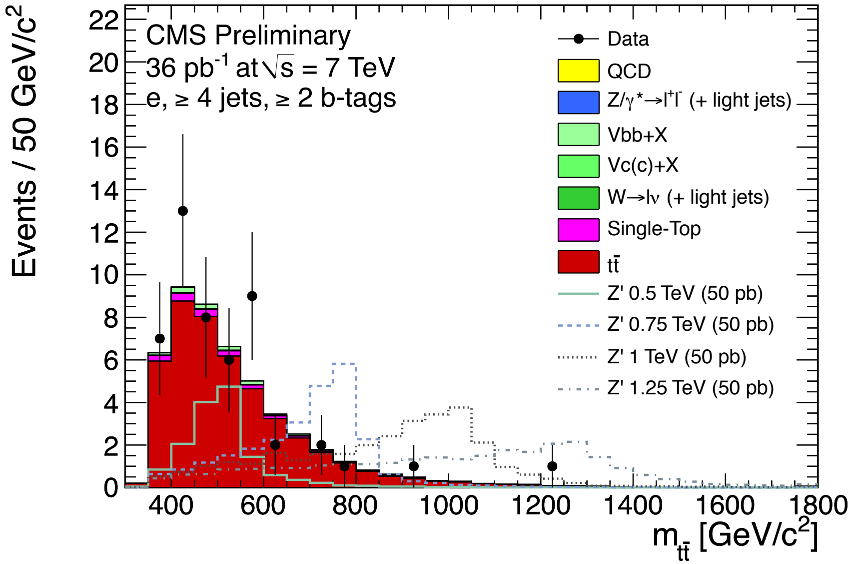


Comparison data and MC – electron case









Statistical description – systematic uncertainties

Several sources of systematic uncertainty have been considered in this analysis.

They can be classified according to whether they are rate-changing or shape-changing.

tag-and-probe with Z→ll data

Uncertainty	**Variation**	**Type**
Luminosity	4%	rate
Electron efficiency (trigger + ID + isolation)	5%	rate
Muon efficiency (trigger + ID + isolation)	5%	rate
$t\bar{t}$ cross section	20%	rate
Single top cross section	30%	rate
W+jets cross section	50%	rate
Ratio Drell-Yan to W cross section	30%	rate
Ratio W/Z+HF to σ(W)	100%	rate
Muon QCD yield	100%	rate
Electron QCD yield	100%	rate
Jet energy scale	p_T,η dependent	shape
Jet energy resolution	10%	shape
Unclustered energy	10%	shape
b tagging efficiency (b jets)	15%	shape
b tagging efficiency (c jets)	30%	shape

Additional theoretical uncertainties on background modeling (factorization Q^2, ISR/FSR, …) have been also considered

Their impact have been estimated by varying the parameters (by a factor of 0.5-2) in MC generations

Statistical description – strategy 1/2

A simultaneous Bayesian integration using the Markov chain Monte Carlo technique was performed on all 8 categories.

Each distribution is modeled combining the MC templates for the signal and all backgrounds generated with MADGRAPH

As reference generic model for new physics, Z' bosons ($\Gamma/M_{Z'}$ = 1%) have been generated with masses between 0.5 and 2 TeV/c^2

$$pdf_{S+B}(m_{t\bar{t}},\vec{\sigma}^r,\vec{\sigma}^s) = N_S(\vec{\sigma}^r,\vec{\sigma}^s)\,pdf_S(m_{t\bar{t}},\vec{\sigma}^s) + \sum_i N_{B,i}(\vec{\sigma}^r,\vec{\sigma}^s)\,pdf_B(m_{t\bar{t}},\vec{\sigma}^s)$$

rate-changing systematic uncertainties

shape-varying systematic uncertainties

The parameter of interest is the Z' cross section. All the other parameters ($\vec{\sigma}^r$, $\vec{\sigma}^s$) are affected by systematic uncertainties and treated as nuisance parameters to describe their impact on the tt mass measurement.

It has been assigned a prior probability to each nuisance parameter:

$\vec{\sigma}^r$ gaussian prior if the relative size < 30%, otherwise log-normal prior

$\vec{\sigma}^s$ template morphing was used

Statistical description – strategy 2/2

Template morphing

It is a bin-wise interpolation between histogram templates (h) at different variations of the respective uncertainty:

the templates are produced by varying each uncertainty by $\pm 1\sigma$ *with respect to the nominal values* (h_0 , $h_{+1\sigma}$, $h_{-1\sigma}$)

The interpolation is performed in each bin using a cubic function to extrapolate between the three input histograms.

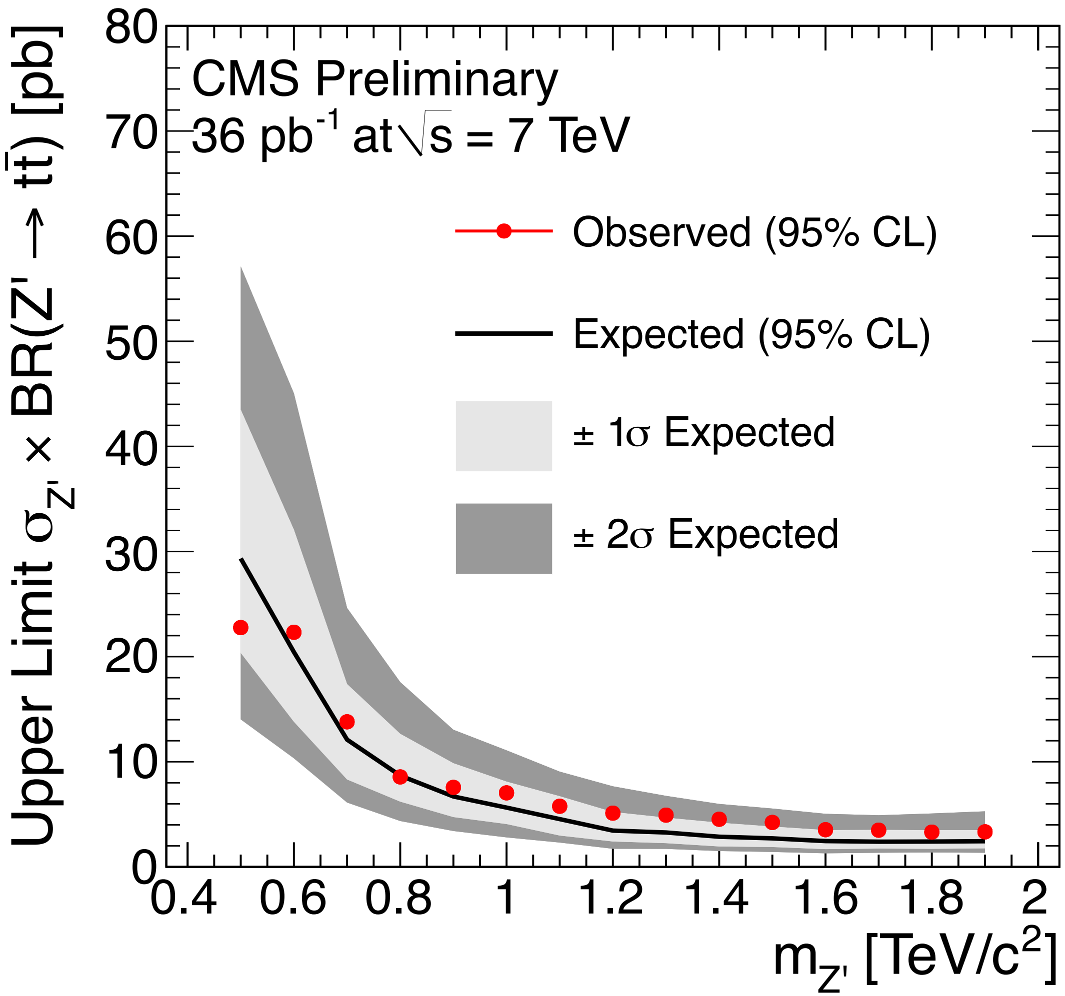
the associated nuisance parameter has a gaussian prior with mean 0 and sigma 1

No significant excess was observed → upper limit on $\sigma(pp \to Z') \times BR(Z' \to t\bar{t})$ as a function of Z' mass.

Upper limit on the Z' cross section

- Upper limits at 95% CL are obtained by integrating the posterior Pdf for the signal cross section up to 95% of its area.
- The expected upper limits have been obtained generating pseudo-experiments with background-only hypothesis.
- The median of the distribution of upper limits defines the expected upper limit.
- The central 68% and 95% areas of the distribution give the 1- and 2-sigma expected upper limits bands.

Statistical description – limit setting on Z' production



Expected limits range

- ~30 pb ($M_{Z'}$ = 0.5 TeV)
- ~3 pb ($M_{Z'}$ > 1.5 TeV)

Observed and expected limits are compatible within one standard deviation except for the 1.5 TeV region where the observed limits are slightly higher than the one sigma band.

Conclusions

- Many extensions of the Standard Model predict gauge interactions with enhanced couplings to the t quark:

    new particles could show up as resonances in the $t\bar{t}$ mass distribution and not in other channels.

- A search for such resonances decaying to top quark pairs has been performed by CMS:

    the semi-leptonic decay of the $t\bar{t}$ pair has been used.

- No significant excess of events above the SM expectation has been observed.

- 95% C.L. cross section upper limits have been set on production of new narrow spin-1 resonances:

    limits range from ~25 pb for resonances with mass of 0.5 TeV/c^2 to 4 pb for 1.5 TeV/c^2 resonances.

Backup

Cross check analysis

Another independent analysis has been performed as a cross check.

Main differences with respect to the other analysis

No events classification → **4 jets are required (2 b-tagged jets)**

Different isolation algorithm ⇒ **2D cut method:** *It is a cut in the (ΔR_{min}, p_{Trel}) plane*

ΔR_{min} is the separation between the lepton and closest jet (pT > 20 GeV/c)

p_{Trel} is the transverse momentum with respect to the jet axis

Different background estimation and statistical treatment

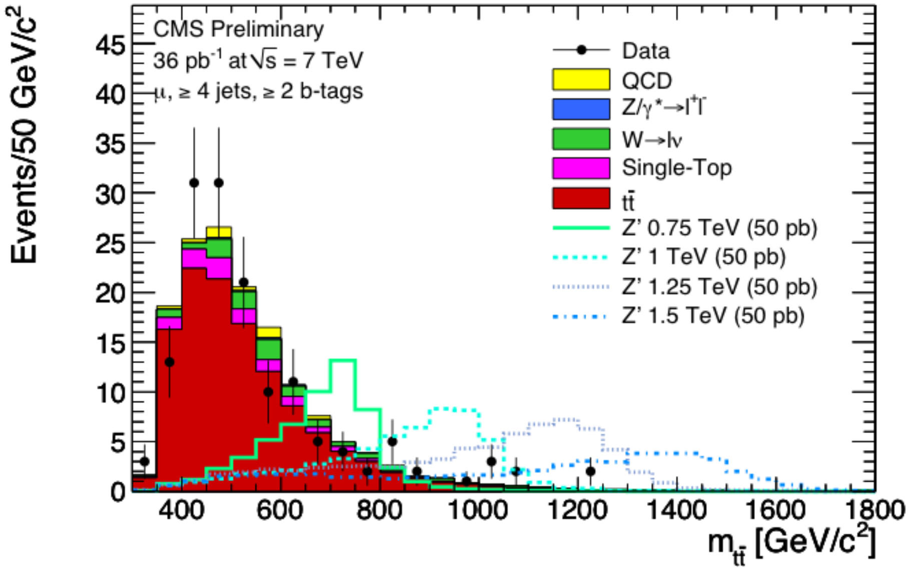
unbinned maximum likelihood fit

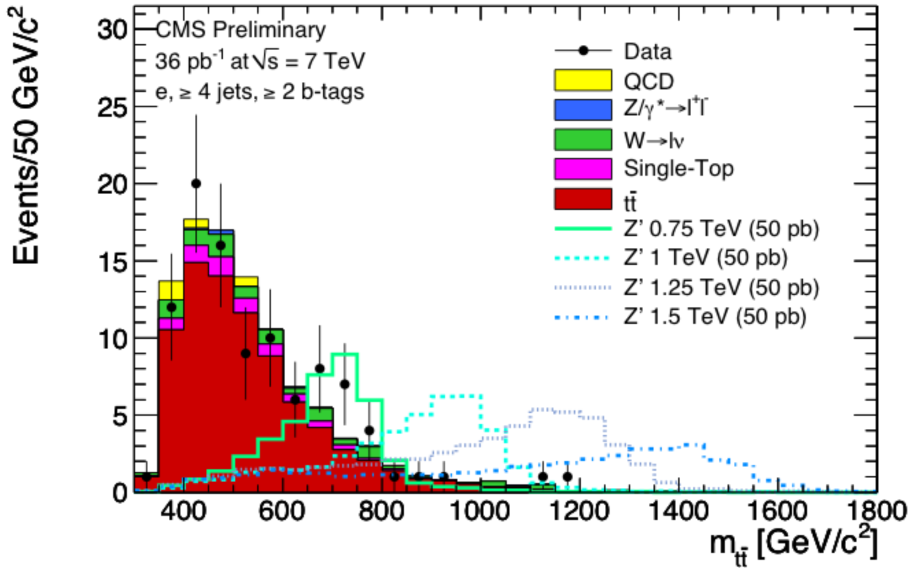
$$L = \frac{e^{-N'}}{N!} N'^{N} \prod_{j=1}^{N} \frac{N_S\, pdf_S + \sum_i N_{Bi}\, pdf_{Bi}}{N'} \qquad N' = N_S + \sum_i N_{Bi}$$

- pdf for background hypothesis is a falling exponential starting from 450 GeV/c^2
- parameters for pdf$_B$ are determined on data fitting control regions defined by requiring no b-tagged jets
- pdf for signal is an analytical fit to MC samples at different Z' masses
- muon and electron channels are simultaneously fitted (same mass for the hypothetic Z')

The cross check analysis has been found consistent with the results here shown

Cross check analysis





Source	$Z'(750)$	$Z'(1000)$	$Z'(1250)$	$Z'(1500)$
MC statistics (semi-mu) (%)	2.7	4.5	2.2	5.4
MC statistics (semi-e) (%)	3.0	2.8	2.4	3.5
Trigger efficiency (μ) (%)	1.2			
Trigger efficiency (e) (%)	1.9			
b-tagging efficiency (%)	30			
Luminosity (%)	11			
Jet-energy scale (pb)	1.2	3.8	2.4	3.9
Signal peak position (pb)	0.3	0.2	0.0	0.3
Signal peak resolution (pb)	0.4	0.2	0.0	0.2
Signal peak tail (pb)	0.2	0.8	0.1	0.3
Background shape (μ) (pb)	0.5	1.3	0.9	2.1
Background shape (e) (pb)	0.4	0.3	0.3	0.4
Alternative background parameterisation (pb)	0.6	1.6	0.1	0.2
Alternative signal parameterisation (pb)	0.8	1.3	0.2	1.8